THE CASE FOR SUBSTANTIAL DUST EXTINCTION AT $z \approx 3$

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Abstract. Estimates of the total metal production rate ($\dot{\rho}_Z$) and star formation rate at $z > 2$ are based on Lyman break systems observed in the rest-frame ultraviolet (UV). These observations are very sensitive to dust obscuration. Here I elucidate and refine the Meurer *et al.* (1997) method for calculating UV obscuration, presenting new relationships which accurately model the dust reprocessing of radiation in local starbursts. The median $\lambda = 1600$ Å obscuration factor is ~ 10 at $z \approx 3$ which is shown to be consistent with other constraints on the high-z $\dot{\rho}_Z$. Two tests are proposed to further constrain $\dot{\rho}_Z$ at these redshifts.

1. Introduction

In their pioneering work, Madau *et al.* (1996; hereafter M96) use Lyman break galaxies in the Hubble deep field (HDF), in conjunction with other surveys, to evaluate the metal production rate $\dot{\rho}_Z$ history of the universe. They find that $\dot{\rho}_Z$ peaked at $z \approx 1$, while at $z \approx 3$ the universe was fairly quiescent much like the present universe. This result assumes dust absorption is negligible. However the high-z observations, in the rest-frame UV, are highly susceptible to the obscuring effects of dust. Although it is now recognized that absorption corrections are significant, the amount of absorption is still under debate. Following from UV observations of local starbursts (Meurer *et al.* 1995, hereafter paper-1) we have argued that the the correction factor to $\dot{\rho}_Z$ is considerable (roughly 15; Meurer *et al.*, 1997; hereafter paper-2), while others (e.g. Madau 1997, hereafter M97; Pettini *et al.* 1997, hereafter P97) prefer fairly modest, $\sim$ factor of three, corrections. As pointed out by M97, what is at stake is more than just the amount of dust in the early universe. If the absorption corrections to $\dot{\rho}_Z$ are low, then hierarchical galaxy formation models are favored, while large corrections at high-z can push back the peak $\dot{\rho}_Z$, favoring monolithic collapse models. Here I take the opportunity to elucidate and refine our technique for estimating the UV attenuation due to dust, reapplying it to high-z galaxies. Further constraints and refinements to the high-z star formation rate are discussed. Finally, I present tests to further constrain the high-z $\dot{\rho}_Z$. Throughout this paper I adopt $H_0 = 50 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$ and $q_0 = 0.5$.

2. Technique

Before proceeding, consider the basic UV absorption and scattering effects of dust. When observing individual stars through small apertures, scattering removes light from the line of sight. This is the geometry used to derive traditional extinction curves. The radiative transfer effects are different when observing galaxies, because firstly, if they are observed through sufficiently large apertures the forward scattered light is recovered, and secondly, the distribution of the dust is important, with clumpy dust screen and mixed and mixed dust geometries producing more absorption per unit reddening than homogeneous foreground screens. The net absorption as a function of wavelength normalized to the optical reddening is the "obscuration curve". For-
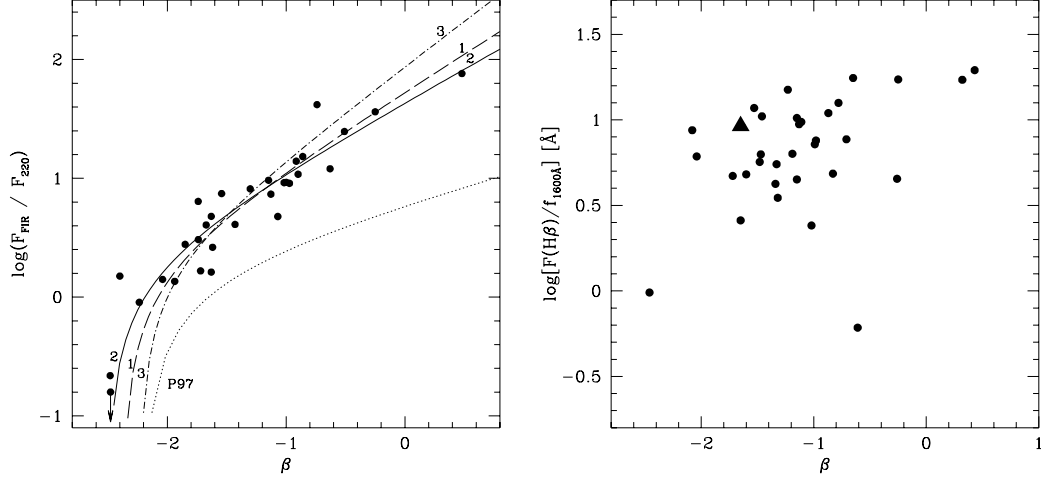
Figure 1 (left). Empirical UV absorption factor compared to UV color β. The fluxes are measured in the FIR by IRAS and in the UV ($\lambda \approx 2300$Å) by HST or IUE. The numbered lines correspond to the three model fits discussed in the text. The dotted line shows the proposed reprocessing model of P97.

Figure 2 (right). Raw Hβ fluxes normalized by UV flux density plotted against β. Circles show local starburst galaxies (Calzetti 1997), while the triangle corresponds to the Lyman break galaxy 0201-C6 (P97).

Table 1

Model	1	2	3	paper-2	P97
Δt [Myr]	80	20	. . .	10	. . .
Obscuration law[a]	C94	0.8C94+0.2K94	C94	C94	SMC
R	3.1	3.1	4.8	3.1	3.1
β_0	−2.33	−2.45	−2.20	−2.53	−2.13
$\langle E(B-V)\rangle^b$	0.28	0.27	0.23	0.33	0.09
$\langle A_{1620}\rangle^b$ [mag]	2.41	2.41	2.51	2.79	1.07

Note:

[a] C94 = Calzetti *et al.* (1994); K94 = Kinney *et al.* (1994).
[b] Evaluated at median $\beta = -1.1$ (paper-2).

tunately dust is not a sink for photons; the absorbed radiation is re-emitted thermally in the far-infrared (FIR). For irradiation by young stellar populations, the dust heating is dominated by UV photons. Hence the ratio of FIR to UV fluxes is an indication of net absorption.

Our analysis is based on the remarkable similarity of Lyman break systems to local starburst galaxies. Figure 1, adapted from papers-1,2 demonstrates that, for local starbursts, UV absorption is correlated with UV spectral slope β ($f_\lambda \propto \lambda^\beta$). This gives us a powerful method of estimating obscuration from UV colors. Figure 1 shows our latest foreground screen model fits to this relationship. We assume that it is due to the reddening of a single intrinsic spectrum, for which we adopt the constant star formation rate models of Leitherer & Heckman (1995; Salpeter IMF with upper mass limit of $100\mathcal{M}_\odot$) or power law spectra models (to extend the range of intrinsic color β_0). For obscuration curves we choose those derived by Calzetti and collaborators (Kinney *et al.* 1994; Calzetti *et al.* 1994; Calzetti, 1997) from starburst spectra with varying amounts of H II reddening. Three fits are shown. Model 1 employs the Calzetti *et al.* (1994) curve, assuming $R \equiv A_V/E(B-V) = 3.1$, and is fit to find the best burst duration Δt. Model 2 is the best fit at fixed $\Delta t = 20$ Myr for obscuration curves varying linearly between that of Calzetti *et al.* (1994) and Kinney *et al.* (1994), again with $R = 3.1$. Model 3 is the best fitting power law spectrum for the Calzetti *et al.* (1994) law with $R = 4.8$ as determined by

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Calzetti (1997). The parameters of the three fits are given in Table 1. I also give the parameters adopted in paper-2, and those adopted by P97 (M97 adopt a similar prescription). The latter does not well model the dust reprocessing of UV radiation observed in starbursts.

Table 1 shows the implications of the models by listing the implied obscuration at $\lambda = 1620$Å, for an observed $\beta = -1.1$ (the rest λ and median color of the HDF Lyman break systems; M96; paper-2). Our new fits all yield $\langle A_{1620} \rangle = 2.46 \pm 0.05$ mag. The fits are nearly model independent since $F_{\mathrm{FIR}}/F_{\mathrm{UV}}$ is the empirical obscuration factor, modulo a correction (of order unity) to $\lambda = 1620$Å. The scatter about the fits, amounting to a factor of 1.6, is the limiting uncertainty of the calibration. Starting with the luminosity function corrected $\dot{\rho}_Z$ estimates of Madau (1996), our models imply corrected values of $\dot{\rho}_Z = 6.4, 2.1 \times 10^{-3}\,\mathcal{M}_\odot\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ for the U and B band dropouts at $z = 2.75, 4.0$ respectively. These estimates are still lower limits because of the unknown contribution from galaxies completely obscured in the UV by dust. Note that this method can not be blindly applied to $\dot{\rho}_Z$ measurements for $z < 2$, because they are drawn from samples not necessarily dominated by starbursts.

3. Other constraints on high-z star formation, and further refinements

• *Extension to rest frame optical fluxes.* Sawicki & Yee (1997; and this volume) fit the $VIJHK$ SEDs of the $z > 2$ galaxies in the HDF with population synthesis models, finding these galaxies to have $E(B - V) \approx 0.2 - 0.3$, and $\Delta t \leq 0.2$ Gyr, consistent with our models (Table 1).
• *FIR-mm background.* Contrary to claims by M97 and P97, the FIR-mm background flux measurements of Puget *et al.* (1996, and others) allow for substantial obscured high-z star formation (e.g. Guiderdoni *et al.* 1997). If the dust temperature $\approx 50°$K, as is the case for typical starbursts, then $\dot{\rho}_Z \leq 0.056\,\mathcal{M}_\odot\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ for $z \geq 2.5$ (Burigana *et al.* 1997).
• *Metal content of the universe.* M97 notes that monolithic collapse models greatly overpredict the metal content of the local universe and the metallicity of damped Lyα systems at $z > 2$. However, these estimates should be considered lower limits since they do not include metals in the inter-galactic medium (IGM) where much of the metals produced by starbursts are likely to be ejected. Mushotzky & Loewenstein (1997) estimate the metal content of the IGM (using ASCA observations) to be 2-5 times that in stars and the ISM (M96) and suggest that the star formation that enriched the IGM occurred either at $z > 1$, or was dust enshrouded. Indeed, the corrected high-z $\dot{\rho}_Z$ agree well with their predictions for $z = 1 - 6$.
• *Low mass stars.* At this conference, Madau suggested that monolithic collapse models overpredict the near infrared (1-2 μm) luminosity density for $z < 1$. This assumes a universal Salpeter IMF slope down to $\lesssim 1\,\mathcal{M}_\odot$. However, there is some evidence that the IMF in starbursts may be biased against low-mass stars (Rieke *et al.*, 1993). Furthermore, the discrepancy is only ~ 0.3 dex, which may partially be accounted for by systematic uncertainties in the modeling.
• *Other refinements.* Two other refinements to our technique are suggested by the work of Dickinson (this conference; also noted by M97, P97) – galaxy by galaxy absorption corrections, and better modelling of the calibration between broadband colors and spectroscopic β. We will address these elsewhere, but the good agreement between our results and those of Sawicki & Yee suggests that these effects are not large.

4. Future constraints

Our obscuration estimates are based on the premise that the Lyman break systems are like local starbursts. They are overestimated if the high-z sample is significantly contaminated by intrinsically redder, non-ionizing populations. Two tests of the starburst hypothesis are feasible:
• *Emission lines.* Detection experiments for recombination lines in high-z galaxies would directly determine whether they are dominated by ionizing populations. P97 note that Hβ has been detected in three Lyman break galaxies and report $L_{\mathrm{H}\beta}$ for one of them, 0201-C6. In Fig. 2

I plot this flux normalized by its UV flux (kindly made available by M. Dickinson) with data from Calzetti (1997) showing that 0201-C6 is similar to local starbursts. More observations, particularly of the reddest systems, are needed to determine the degree of contamination by non-starbursts.

• *Radio continuum.* If obscured starbursts emit primarily in the FIR, then we may hope to detect them in radio continuum via the radio-FIR correlation. Fomalont's *et al.* (1996) deep 8.4GHz image of the HDF has a detection threshold of 12 μJy corresponding to $L_{bol} \approx 10^{12.8} L_{\odot}$ for $z = 3$ and an assumed continuum index $\alpha = 0.7$ ($f_{\nu} \propto \nu^{\alpha}$). While none of the galaxies detected by Fomalont *et al.* are Lyman break systems, only one of the HDF U dropouts has L_{bol} large enough that it could (barely) have been detected. Deeper radio imaging (perhaps at lower frequencies) should better constrain the FIR emission of high-z starbursts.

5.   Summary

Our view of cosmological evolution is obscured by dust, particularly at $z > 2$ where the observations are in the rest-frame UV. The method presented here of estimating the UV dust obscuration factor accurately models the dust reprocessing of radiation in local starburst galaxies. With the assumption that Lyman break galaxies are like local starbursts I estimate a median correction factor of ~ 10 to $\dot{\rho}_Z$ at $z \sim 3$. The corrected $\dot{\rho}_Z$ estimates are consistent with other constraints on the high-z star formation rate. Two tests of these results are feasible with existing technology. Observations of rest frame Balmer emission provide a test of the starburst assumption, while deep radio imaging can provide an independent estimate of the reprocessed UV emission.

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